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A comparative experimental study on the mechanical properties of cast-in-place and precast concrete-frozen soil interfaces

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Abstract. The mechanical properties of the concrete-frozen soil interface play a significant role in the stability and service performance of construction projects in cold regions. Current research mainly focuses on the precast concrete-frozen soil interface, with limited consideration for the more realistic cast-in-place concrete-frozen soil interface. The two construction methods result in completely different contact surface morphologies and exhibit significant differences in mechanical properties. Therefore, this study selects silty clay as the research object and conducts direct shear tests on the concrete-frozen soil interface under conditions of initial water content ranging from 12% to 24%, normal stress from 50 kPa to 300 kPa, and freezing temperature of -3°C. The results indicate that (1) both interface shear stress-displacement curves can be divided into three stages: rapid growth of shear stress, softening of shear stress after peak, and residual stability; (2) the peak strength of both interfaces increases initially and then decreases with an increase in water content, while residual strength is relatively less affected by water content; (3) peak strength and residual strength are linearly positively correlated with normal stress, and the strength of ice bonding is less affected by normal stress; (4) the mechanical properties of the cast-in-place concrete-frozen soil interface are significantly better than those of the precast concrete-frozen soil interface. However, when the water content is high, the former's mechanical performance deteriorates much more than the latter, leading to severe strength loss. Therefore, in practical engineering, cast-in-place concrete construction is preferred in cases of higher negative temperatures and lower water content, while precast concrete construction is considered in cases of lower negative temperatures and higher water content. This study provides reference for the construction of frozen soil-structure interface in cold regions and basic data support for improving the stability and service performance of cold region engineering.

Keywords: cold region engineering; concrete-frozen soil interface; frozen soil; interface bond strength; mechanical properties; peak strength; residual strength; silty clay

1. Introduction

Frozen soil refers to soil or rock that maintains a temperature at or below 0°C and contains ice. In China, which ranks as the world's third-largest frozen soil country, frozen soil and seasonal areas cover 21.5% and 53.5% of the national land area, respectively (Tai *et al.* 2021). with the rapid economic development, numerous large-scale projects have been constructed in cold regions, such as the Qinghai-Tibet Railway and the Sichuan-Tibet Highway. However, frozen soil is prone to instability, leading to issues like frost heave and thaw settlement caused by temperature changes. As a result, it is unsuitable as a subgrade soil for engineering purposes (Lyazgin *et al.* 2004, Fischer *et al.* 2010, Dore *et al.* 2016, Kandalai *et al.* 2023).

In various cold region engineering projects, concrete-frozen soil structures, such as pile foundations and canal linings, are commonly employed. The mechanical properties of the interface between these concrete structures and frozen soil are crucial for transferring stress and deformation, significantly influencing the stability and service life of engineering structures (He *et al*. 2020, Zhang *et al*. 2022). The concrete-frozen soil interface is often susceptible to severe frost damage, leading to issues such as pile foundation frost heaving and canal lining detachment (Farquharson *et al*. 2019, Tang *et al.* 2020). Therefore, it is essential to clarify the mechanical properties and deformation mechanism of the concrete-frozen soil interface to analyze engineering stability, structural bearing capacity, and service performance. In cold region engineering, the construction process of cast-in-place concrete is widely employed, in comparison to precast concrete, the casting of concrete generates thermal disturbances on frozen soil due to the temperature of the concrete and the heat of hydration, these disturbances induce varying degrees of melting and refreezing processes in the frozen soil, the interface roughness is changed, subsequently resulting in significant changes in the mechanical properties of the concrete-frozen soil interface.

These changes further affect the stability and load-bearing capacity of the engineering structures, therefore, it

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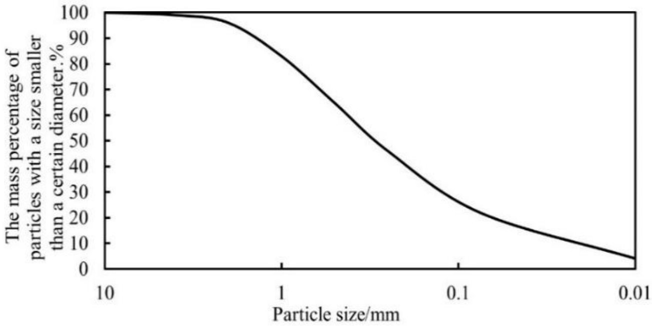


Fig. 1 Particle grading curve of test soil samples

is necessary to study the mechanical properties of cast-in-place concrete-frozen soil interface. However, currently there are few researches on mechanical properties of cast-in-place concrete-frozen soil interface, which is common in cold area engineering.

The investigation into the mechanical properties of the frozen soil-structures interface has yielded significant results domestically and internationally. Biggar *et al*. (1993), Ladanyi (1995) showed that the interface strength was comprehensively affected by multiple factors, and proposed to describe the shear strength of the frozen interface with the Mohr-Coulomb formula. Ko *et al*. (2011) studied the influence of different test materials on the freezing strength of the frozen soil-structure interface through the indoor direct shear test. Liu *et al*. (2014) explored the mechanical behavior of frozen soil-concrete interface, identified the effects of various factors on interface shear strength, and proposed an empirical formula for strength calculation. Bondarenko *et al*. (1975), He *et al*. (2018) delved into the characteristics and formation mechanism of freezing strength in the frozen soil-structures interface, breaking down interface strength into ice cementing strength and residual strength. Abdulghader et al. (2019) explored the shear strength characteristics of the pile-frozen soil interface based on the surface roughness coefficient. Xiong *et al*. (2021) summarized the influence of temperature, water content, and normal stress on the freezing strength at the frozen soil-concrete interface, while analyzing the underlying mechanism behind the freezing strength variations. Additionally, Sun *et al*. (2021) examined the freezing strength in frozen soil-structure interfaces through direct shear tests, investigating the significance of different factors' influence on the strength. Park *et al*. (2022) applied punch shear test to estimate the adfreezing strength of frozen soil-structure interface, showing the adfreezing strength increased with a decrease in the temperature and increase in the initial water content. Zhao *et al.* (2022) analyzed the effects of temperature and water content on the mechanical properties of frozen soil-concrete pile interface, establishing a constitutive model to describe the shear stress-displacement relationship of the interface. Guo *et al*. (2023) investigated the strength characteristics of frozen soil-structures interface under the interaction of multiple factors. However, previous research on the frozen soil-structures interface has predominantly focused on the precast concrete-frozen soil interface, overlooking the crucial distinctions in properties between precast and cast-in-place concrete. The unique characteristics of cast-in-place concrete can induce thermal disturbance to the frozen soil during construction, making it crucial to investigate the mechanical characteristics of the concrete-frozen soil interface under thermal disturbance. additionally, it is essential to compare the similarities and differences between the two types of concrete-frozen soil interfaces and assess whether the conclusions drawn from previous studies on precast concrete can be applied to the cast-in-place concrete interface. Despite these being critical issues in the freeze strength of the concrete-frozen soil interface, there is currently few relevant studies. Ji *et al*. (2017) investigated the strength of the cast-in-place concrete-frozen soil interface and noted that thermal disturbance significantly changes the interface's roughness, consequently affecting its mechanical properties. Zhang *et al.* (2022) analyzed the shear mechanical characteristics and force deformation mechanism of the cast-in-place concrete-high-temperature frozen soil interface, established a constitutive model based on the interface's microscopic deformation mechanism. However, these studies did not extensively explored the strength characteristics of the cast-in-place concrete-frozen soil interface or analyze the differences in mechanical properties between the cast-in-place and precast concrete-frozen soil interfaces.

Building upon the existing findings, the objective of this study is to extend the understanding of the mechanical characteristics of the cast-in-place concrete-frozen soil interface and compare them with the precast concrete-frozen soil interface. To accomplish this objective, a series of direct shear tests will be conducted on both cast-in-place and precast concrete-frozen soil interfaces, with the initial water content as the variable. By analyzing and comparing the mechanical properties and differences of each interface, this research aims to provide a valuable reference and establish a theoretical foundation for the design and construction of engineering projects in cold regions.

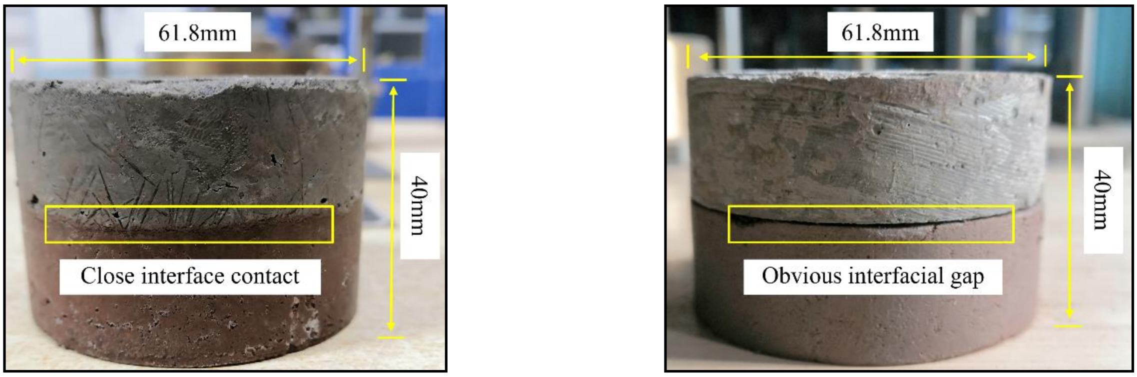
2. Test materials and methods

2.1 Sample preparation

Considering the complications in result analysis arising from the natural state of undisturbed soil, remolded soil

Table 1 Basic physical properties of soil samples

Soil quality	Liquid limit /%	Plastic limit /%	Plasticity index	Optimal water content/%	Maximum dry density/g/cm^3
Silty clay	28.18	16.60	11.58	11.89	1.96



(a) Cast-in-place concrete-frozen soil sample (b) Precast concrete-frozen soil sample

Fig. 2 Concrete-frozen soil shear samples

samples from Ya'an, China (100°43'42″E, 31°52'25″N) were utilized for the tests. Wet soil samples were collected and subjected dried in an oven at 105℃ for 24hours. The dried soil samples were crushed and sieved through a 2 mm mesh for future use. Physical property tests were conducted following the standard soil testing method (GBT 50123-2019), and the measured physical parameters are presented in Table 1. The particle size distribution curve is illustrated in Fig. 1, and the experimental soil sample was identified as a silty clay.

The sample preparation process involves three main steps, preparing precast concrete samples, preparing frozen soil samples, and preparing concrete-frozen soil samples. The sample preparation method employed in this study draws upon similar sampling techniques used in previous researches (Ji *et al*. 2017, Zhang *et al*. 2022b).

2.1.1 Precast concrete sample preparation

The preparation of precast concrete samples involves several essential steps, (1) Molds with dimension of 61.8 mm×20 mm were utilized, and the inner walls were coated with Vaseline to facilitate demolding. (2) A concrete mixture was created by combining PO42.5 Ordinary Portland Cement, river sand, and crushed stone, with a mixing ratio of 1.5:2:1:0.75 for cement, crushed stone, sand and water respectively. The crushed stone used ranged in size between 2 mm-5 mm in size. (3) The mixed concrete was poured into the molds and compacted thoroughly to achieve a 20 mm high sample. (4) The concrete samples were cured according to specifications. (5) The cured concrete samples were removed from the molds and stored for future use.

2.1.2 Frozen soil sample preparation

The frozen soil samples preparation involves four steps, (1) Soil samples were prepared according to their designed water content and sealed for 24 hours to ensure even water distribution. (2) Using molds with dimensions of 61.8 mm×20 mm, the inner walls were coated with Vaseline. The soil samples were layered, compacted, and the surface was smoothed with a controlled dry density of 1.68 g/cm^3. (3) Glass sheets were placed on both sides of the mold filled with soil samples, and the mold was tightly wrapped with cling film. (4) The prepared soil samples were rapidly frozen at -20℃ for 12 hours in a precision-controlled freezer. Subsequently, the freezer temperature was adjusted to -3℃ and maintained for 24 hours to keep the samples at a constant temperature.

2.1.3 Concrete-frozen soil sample preparation

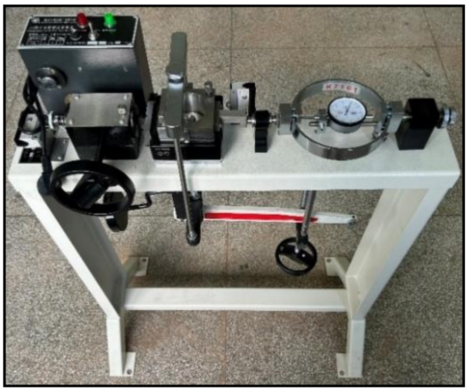
The preparation of concrete-frozen soil samples included both the cast-in-place and precast methods.

For cast-in-place concrete-frozen soil samples, the process involves three steps, (1) A testing chamber with a mold size of 61.8 mm×40 mm was used, with the bottom sealed using a glass sheet, and precast frozen soil samples were placed inside for later use. (2) The previously mentioned concrete mixture were poured into the chamber, compacted to form 40mm high samples, and then covered with a glass sheet. The entire setup was wrapped with cling film and stored at -3℃; (3) After 28d curing period, the samples were removed from the molds to create the cast-in-place concrete-frozen soil samples (Fig. 2(a)).

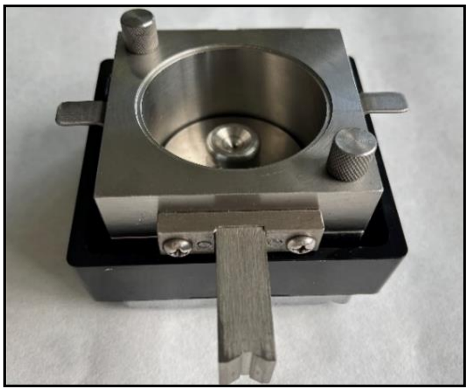
To prepare precast concrete-frozen soil samples, the precast concrete samples and frozen soil samples were stacked to form 61.8 mm×40 mm specimens. The two components were pressed together to ensure tight contact (Fig. 2(b)), wrapped in cling film, and stored at -3℃ for 28d.

2.2 Test method and design

To investigate the mechanical properties of the concrete-frozen soil interface, the ZJ-type strain-controlled direct



(a) ZJ strain controlled direct shear instrument



(b) Test shear box

Fig. 3 Direct shear instrument and shear box

Table 2 Shear test conditions table

Working condition	Initial water content /%	Freezing temperature /°C	Shear rate /mm/min	Normal stress /kPa
1	12	-3	2.4	50
2				100
3				200
4				300
5	15	-3	2.4	50
6				100
7				200
8				300
9	18	-3	2.4	50
10				100
11				200
12				300
13	21	-3	2.4	50
14				100
15				200
16				300
17	24	-3	2.4	50
18				100
19				200
20				300

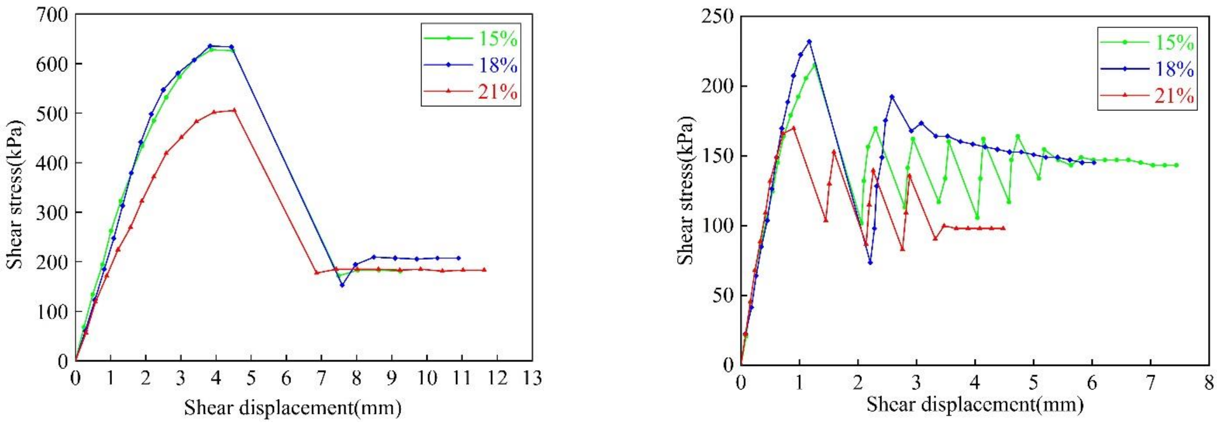
shear device produced by Nanjing Ning xi Soil Limited Company (Fig. 3(a)) and the test shear box (Fig. 3(b)) were utilized in this study. Four normal stresses (50 kPa, 100 kPa, 200 kPa, and 300 kPa) were selected for the tests, and a shear rate of 2.4 mm/min was set to minimize the thermal disturbance of the interface ice film caused by the external environment. To reduce errors, the direct shear tests were conducted within a constant temperature chamber and chose the colder winter months. Additionally, pre-cooling multiple dry shear boxes before the tests, these boxes were frozen and used in rotation to minimize the impact of thermal disturbance. Three parallel tests were performed for each working condition.

Considering the soil's liquid and plastic limits and the optimal water content, five different initial water contents were selected (12%, 15%, 18%, 21%, and 24%). The samples were maintained at -3℃ during the freezing process, the specific experimental design is shown in Table 2. To compare and analyze the mechanical property differences between the cast-in-place concrete-frozen soil and precast concrete-frozen soil interfaces, both types were tested under the same working conditions.

3.Test results and analysis

3.1 Analysis of shear stress-shear displacement curve characteristics

Fig. 4 depicts shear stress-displacement curves for the concrete-frozen soil interface at a normal stress of 300 kPa and a freezing temperature of -3°C under varying water contents (15%, 18%, and 21%). The study reveals a strain-softening behavior in the strength of the concrete-frozen soil interface, marked by rapid shear stress increase, post-peak shear stress softening, and residual stable stages. Before reaching the peak shear stress, the ice bonding effect at the interface is noteworthy. It is primarily undertaken by



(a) Cast-in-place concrete-frozen soil interface (b) Precast concrete-frozen soil interface

Fig. 4 Interface shear stress-shear displacement curve with different water content

(a) Cast-in-place concrete-frozen soil interface (b) Precast concrete-frozen soil interface

Fig. 5 Direct shear samples after interface deformation

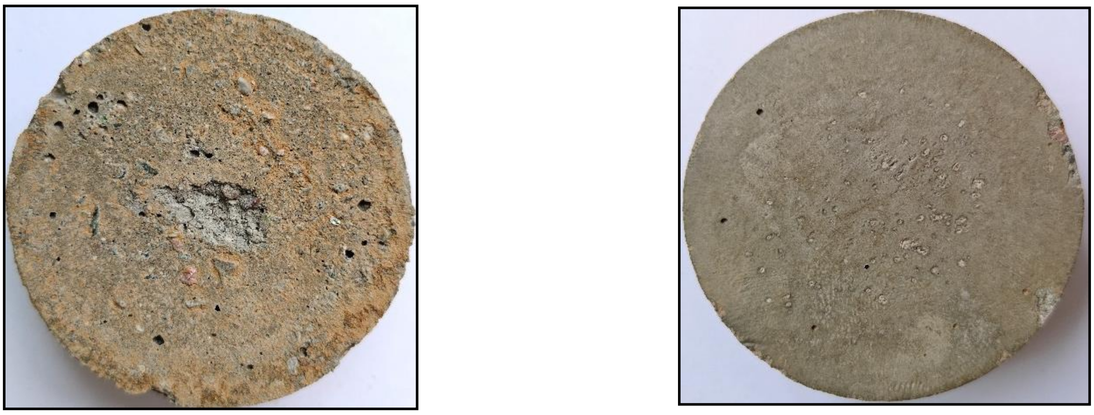
the combined actions of ice bonding force and interparticle cohesion for shear deformation. As shear displacement increases, surpassing the shear strength strain of the interface, there is a sharp drop in shear stress, and the curve exhibits a strain-softening behavior. This phenomenon is mainly attributed to the substantial destruction of the interface ice bonding force, resulting in brittle failure. As the experiment progresses, the curve stabilizes after the softening phase. At this juncture, the interface's ice bonding effect is nearly entirely lost, and the interface strength is predominantly provided by sliding friction.

From Fig. 4, notable differences can be observed in the shear stress-strain curves between the cast-in-place and precast concrete-frozen soil interfaces. The precast concrete-frozen soil interface displayed significant ice re-bonding and stress cycle softening phenomena, mainly attribute to differences in surface roughness.

Fig. 5 shows the direct shear specimens after interface deformation, where it is evident that the cast-in-place concrete side exhibits more adhered soil particles compared to the precast concrete side, where soil particles are not prominently observed. In Fig. 6(a), a concave-convex surface is observed when concrete is poured into frozen soil with an 18% water content, this phenomenon is attributed to heat during casting and heat of hydration, producing a "melting-refreezing" process at the frozen soil interface, this process increases the depth and width of the embedding of concrete and soil particles, resulting in an enlarged interface roughness. The process changes the mechanism of particle interaction, beyond sliding, involves particle fracture, rotation, and rolling, causing the shear plane to move down and up and the formation of a shear band, this process severely disrupts the ice crystal state at the interface, leading to scattered ice crystals with a significantly reduced content. Additionally, the increased interface roughness diminishes the area available for re-cementation, making re-cementation hard to happen.

The precast concrete-frozen soil interface appears smooth (Fig. 6(b)), with weak interlocking effect among particles. The shear process resembles sliding friction, where particles primarily undergo relative sliding without causing significant damage to the soil structure, no shear band is formed, so there are more residual ice crystals at the interface. In sub-zero temperatures, the presence of residual ice crystals, along with unfrozen water, facilitates the rapid occurrence of multiple re-cementation at the interface.

The softening and decay of shear stress result from the generation of heat due to interface damage and friction during shear failure, causing a reduction in ice crystal melting and weakening re-cementation effects. Simultaneously, considering the displacement at which the interface reaches peak strength, under each water content, the cast-in-place concrete-frozen soil interface achieves



(a) Cast-in-place concrete-frozen soil interface (b) Precast concrete-frozen soil interface

Fig. 6 Photos of concrete-frozen soil interface (concrete side)

peak shear stress at approximately 4 mm to 5 mm, while the precast concrete-frozen soil interface reaches peak shear stress at ≤2 mm.

3.2 Analysis of interface freezing strength characteristics

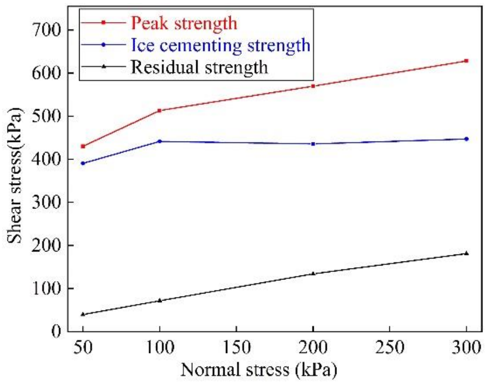
According to previous studies (He *et al*. 2018) the peak strength of the concrete -frozen soil interface consists of two main components: ice cementing strength and residual strength, the latter being composed of particle adhesion and friction. Using this theory, the peak strength, ice cementing strength, and residual strength of the interface were analyzed separately.

Fig. 7(a) shows the trends of the peak shear strength, ice cementing strength, and residual strength of the cast-in-place concrete-frozen soil interface at different normal stresses, with a freezing temperature is -3℃ and initial water content of 15%. It can be observed that increasing the normal stress from 50 kPa to 300 kPa leads to an increase in peak strength from 430.01 kPa to 628.04 kPa and an increase in residual strength from 39.61 kPa to 181.06 kPa, both of which are positively correlated with normal stress. The ice cementing strength is not significantly affected by normal stress, particularly when the normal stress is greater than 100 kPa. This suggests that the normal stress primarily affects the residual strength of the interface, and the frictional force of the interface is greatly influenced by normal stress, while the effect of normal stress on the ice cementing strength of the interface is not evident.

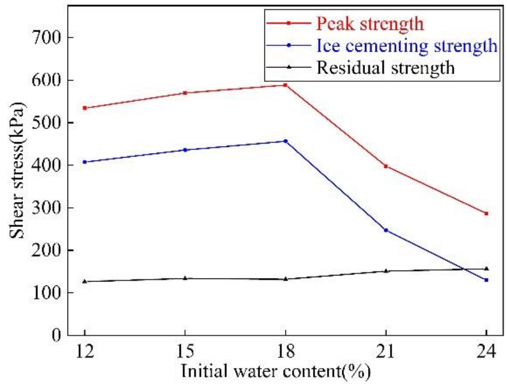
Fig. 7(b) illustrates the variation patterns of the peak shear strength, ice cementing strength, and residual strength of the cast-in-place concrete-frozen soil interface at different water contents, with a freezing temperature is -3℃ and a normal stress of 200 kPa. It can be observed that the peak strength of the interface is consistent with the variation of ice cementing strength with water content, both showing an increasing trend, reaching peak values of 588.43 kPa and 456.41 kPa, respectively, at around 18% water content. When the water content increases from 12% to 24%, the residual strength slightly increases from 126.36 kPa to 156.54 kPa, indicating that the effect of water content on the peak strength of the interface is mainly based on the influence of water content on the ice cementing strength, while the impact on the residual strength is negligible.

The peak strength of the interface under various normal stresses follows a pattern of initial increase and subsequent decrease with increasing water content. On one hand, as the water content rises from 12% to the peak water content, the formation of bonded ice during the interface refreezing increases, thereby enhancing interparticle bonding forces. meanwhile, the introduction of ice particles creates irregular contacts between interface particles, reducing interparticle shear sliding and increasing frictional forces between particles. With a continued increase in water content, and as the freezing ratio of water remains constant under constant temperature, the liquid water content at the interface also increases. At this stage, a larger amount of liquid water acts as a lubricant, diminishing the ice bonding forces between particles. On the other hand, the increase of water content will affect the surface roughness of concrete at lower water content, the increased ice content in frozen soil raises its thermal conductivity, the thermal intrusion ability of concrete into frozen soil is promoted, enhancing the mechanical interlocking effect between concrete particles and soil particles, leading to an increase in interface roughness. During shear, the soil at the interface undergoes more intense movement, resulting in a more pronounced process of soil fragmentation and the filling of rough grooves with soil particles. This process requires a greater external force to perform work. As the water content continues to increase from the peak water content, the ice content at the frozen soil interface increases, forming a dense ice film layer, the heat of phase transition is increased, and a substantial amount of ice crystals consumes the heat introduced by the concrete, hindering the thermal intrusion ability of concrete into frozen soil. The mechanical interlocking effect between particles is impeded, leading to a reduction in interface roughness and a decrease in frictional forces. Consequently, the interface peak strength exhibits a trend of initial increase followed by a subsequent decrease under the combined influence of roughness, bonded ice, and liquid water.

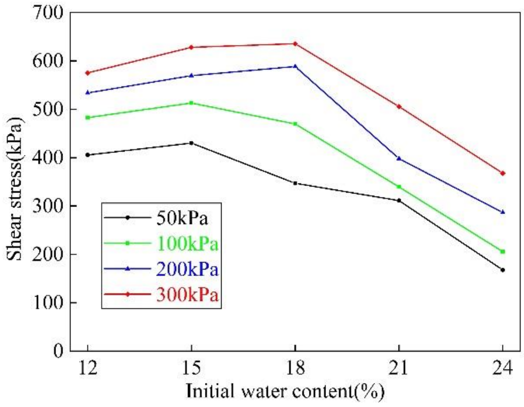
Comparing different normal stresses, the water content is different when the strength reaches the peak, as shown in



(a) Fig. of variation of each strength value with normal stress



(b) Fig. of variation of each strength value with initial water content



(c) Change of peak strength under different normal stresses

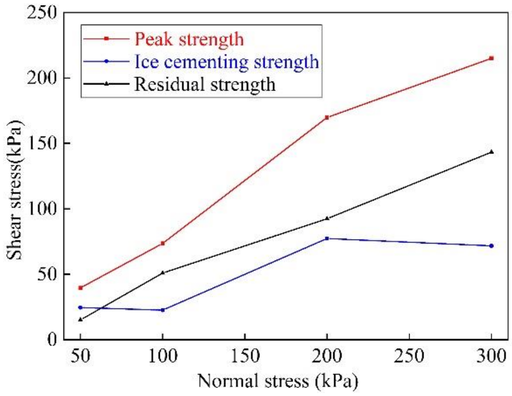
Fig. 7 Peak strength of cast-in-place concrete-frozen soil interface under different normal stress and water content, Variation law of ice cementing strength and residual strength

Fig. 7(c). Peak strength is achieved at around water content 15%for 50 kPa and 100 kPa, while for 200 kPa and 300 kPa, the peak strength is attained at around water content 18%. This discrepancy is attributed to the variation in interface roughness, which initially increases and then decreases with water content. When the water content increases from 15% to 18%, the interface roughness is maximized. At this point, the significant increase in normal stress notably enhances the contribution of frictional forces to the interface strength.

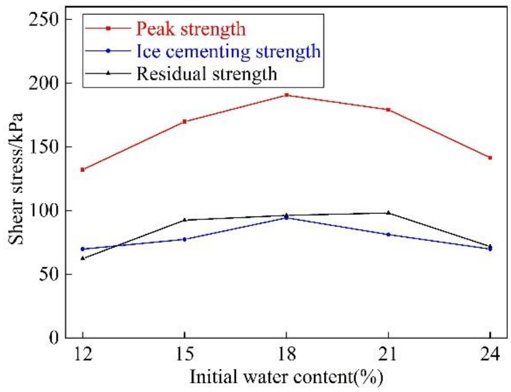
Fig. 8 illustrates the variations in peak shear strength, ice cementing strength, and residual strength of the precast concrete-frozen soil at different normal stresses, with an initial water content of 15% and a freezing temperature of -3℃. The Fig. 8(a) shows that as the normal stress increases from 50 kPa to 300 kPa, both the peak strength and residual strength exhibit significantly increases, ranging from 39.61 kPa to 215.00 kPa and from 15.09 kPa to 143.34 kPa, respectively. These values are positively correlated with normal stress and demonstrate substantial numerical variations. Furthermore, the ice cementing strength also increases slightly with normal stress, although to a lesser extent. These results indicate that normal stress mainly affects the interface residual strength, while exerting a relatively smaller impact on the ice cementing strength. This trend is similar to what was observed at the cast-in-place concrete-frozen soil interface.

Fig. 8(b) displays the variations in peak shear strength, ice cementing strength, and residual strength of the precast concrete-frozen soil interface at different water contents, with a normal stress of 200 kPa and a freezing temperature of -3℃. The figure shows that the peak strength initially increases and then decreases with increasing water content, reaching a peak value at approximately 18% water content.

This behavior can be attributed to the increased presence of ice crystal particles and ice molecules participating in the formation of interface bonding force as the water content rises from 12% to 18%. This is because when the water content increases from 12% to 18%, there is an increase in the ice crystal particles formed at the interface, the greater number of ice molecules participating in the formation of interface bonding forces enhances the ice bonding strength, leading to an increase in peak strength. As the water content further increases, a denser ice film is formed at the interface, additionally, the excessive presence of residual liquid water at the interface fills the voids, the two factors contribute to a reduction in interface roughness with increasing water content, moreover, the increased content of liquid water decreases the bonding strength between ice and the interface, above results in a decrease in peak strength. Analysis of Fig. 8(b) indicates the interface ice bonding strength and residual strength also exhibit slight variations with changes in water content. that water content simultaneously influences both interface ice bonding

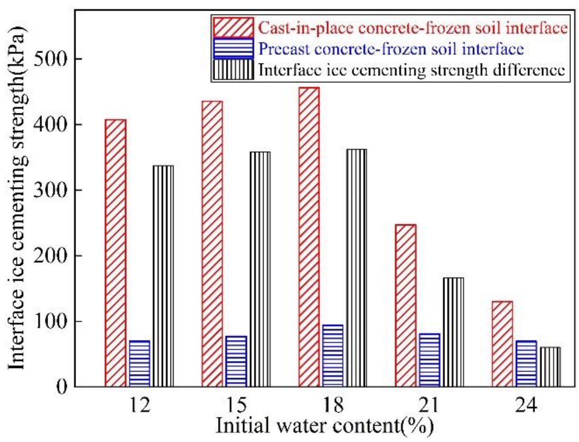


(a) Fig. of variation of each strength value with normal stress

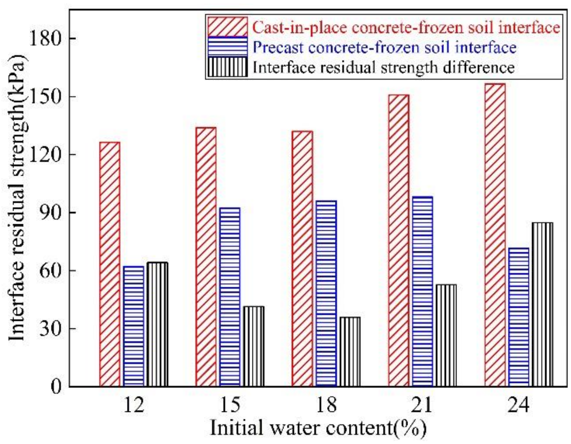


(b) Fig. of variation of each strength value with initial water content

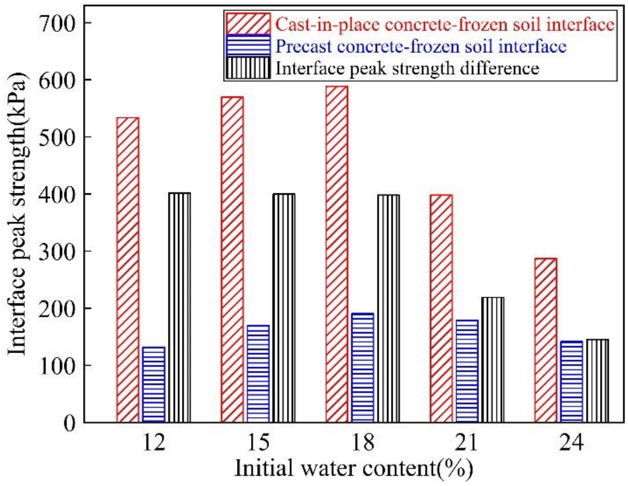
Fig. 8 Peak strength of precast concrete-frozen soil interface under different normal stress and water content, variation law of ice cementing strength and residual strength



(a) Comparative analysis of ice cementing strength



(b) Comparative analysis of residual strength



(c) Comparative analysis of peak strength

Fig. 9 Comparison and analysis of strength of cast-in-place/precast concrete-frozen soil interface

strength and residual strength, leading to variations in interface peak strength.

Fig. 9 compares the peak strength, ice cementing strength, and residual strength of the cast-in-place and precast concrete-frozen soil interfaces at -3℃ and 200 kPa. As shown in Fig. 9(a), the ice cementing strength of the cast-in-place concrete-frozen soil interface is more susceptible to changes in water content compared to the precast concrete-frozen soil interface. Specifically, when the water content rises from 18% to 24%, the ice cementing strength of the cast-in-place concrete-frozen soil interface decreases from 456.41 kPa to 130.13 kPa, a reduction of

326.28 kPa. This can be attributed to the increase in unfrozen water content, resulting in a decrease in peak cohesion at the interface. Conversely, the ice cementing strength of the precast concrete-frozen soil interface exhibits relatively low sensitivity to variations in water content.

Fig. 9(b) shows that the effect of water content on the residual strength of both interfaces is relatively small. The slight increase in residual strength is mainly due to the recrystallization of some ice crystals following the shear failure of the interface. The results indicate that under the same conditions, the cast-in-place concrete-frozen soil interface exhibits higher peak strength, ice cementing strength, and residual strength compared to the precast concrete-frozen soil interface, as shown in Fig. 9(c). This suggests that the mechanical performance of the cast-in-place concrete-frozen soil interface surpass that of the precast concrete-frozen soil interface. However, with further increases in water content, particularly when the water content exceeds 18%, the mechanical properties of the two interfaces gradually deteriorate. The difference in peak strength between the two interfaces decreases diminishes significantly with increasing water content, indicating a convergence of their peak strengths. This trend may be attributed to the significant increase in ice crystals at the interface with rising water content, resulting in the separation of soil and concrete particles at the interface and ultimately leading to a decrease in interface strength, approaching the strength of ice.

3.3 Analysis of interface strength parameter characteristics

Fig. 10 shows the interface peak shear strength curves of the cast-in-place and precast concrete-frozen soil interfaces under different water content conditions. The horizontal axis represents the peak strength. The curves demonstrate an overall linear variation.

The Mohr-Coulomb strength criterion is widely applied in research on the freezing strength of concrete-frozen soil interface due to its high adaptability, as depicted in Eq. (1).

$$\tau_f = \sigma \tan\varphi + c \tag{1}$$

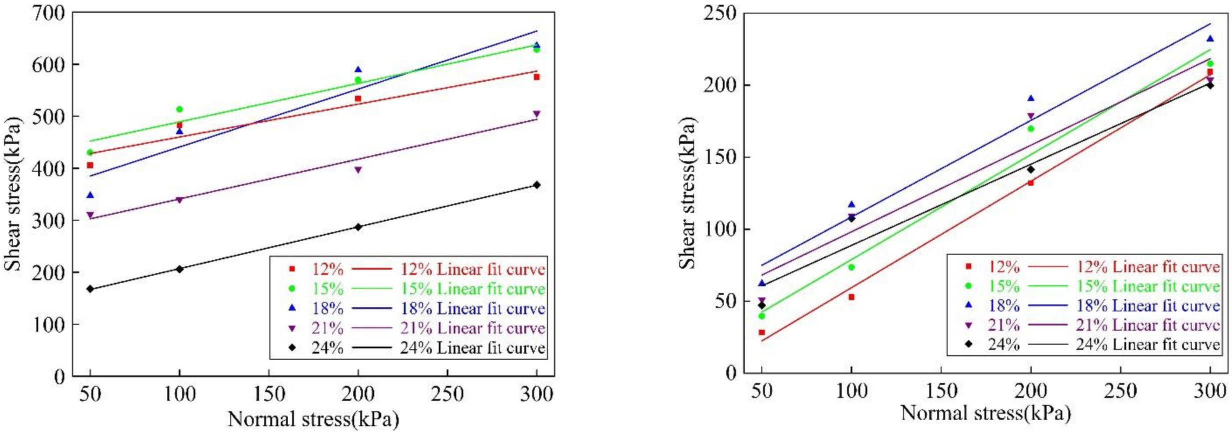
where, the τ_f is Shear strength (kPa), the c is Cohesion(kPa), the σ is Normal stress(kPa), the φ is Friction angle (°).

In this study, the Mohr-Coulomb criterion was employed to fit the τ_f - σ curves of specimens under different working conditions. The results exhibited favorable correlations, enabling the analysis of interface strength characteristic parameters based on the Mohr-Coulomb criterion. These parameters, which describe the peak and residual strengths of the interface, can be defined as interface cohesion, interface friction angle, residual cohesion, and residual friction angle, respectively, when utilizing this equation.

Table 3 presents the characteristic parameters of the peak strength at the interface between cast-in-place concrete and precast concrete-frozen soil interface under different water contents at a freezing temperature of -3°C. As shown in the table, the peak cohesion of the interface between cast-in-place concrete-frozen soil slightly increases from 396.57 kPa to 414.95 kPa as the water content increases from 12% to 15%. However, when the water content exceeds 15%, the peak cohesion decreases with increasing water content, dropping from 414.95 kPa to 126.58 kPa. Regarding the precast concrete-frozen soil interface, the peak cohesion initially increases and then decreases with the increase in water content, reaching a maximum of 41.43 kPa at a water content of 18%. The change patterns of the peak cohesion for both interfaces exhibit similarities, and analyze that frozen soil is a particle complex (Ghoreishian Amiri *et al.* 2022), the mechanical behavior of the interface is jointly influenced by the content of ice and liquid water. When the water content is low, the interface liquid water content is also low, and the dominating factor is the ice bonding force. As the water content increases, the freezing ratio of water remains constant under constant temperature. the liquid water content at the interface increases, affecting the bonding between ice and the interface, therefore, the peak cohesion increases first and then decreases.

Furthermore, Table 3 demonstrate that the peak friction angle of the cast-in-place concrete-frozen soil interface initially increases and then decreases with the increase in water content, this is attributed to the trend of interface roughness, which initially increases and then decreases with the water content of frozen soil. With the largest increase occurring from 15% to 18% water content, reaching a maximum value of 48.10 °. This indicates that the interface roughness is highest at this water content. Therefore, the peak strength of the interface under high normal stress is achieved at a water content of around 18%. In addition, the peak friction angle of the precast concrete-frozen soil interface decreases from 36.49° to 29.41° with increase in water content, the underlying cause is the increase in water content, leading to a higher number of ice crystals at the interface. These ice crystals fill the voids along with liquid water, serving as a lubricant and reducing frictional forces.

When the strength of the concrete-frozen soil interface reaches a stable residual strength, significant displacement deformation occurs, leading to the destruction of interface cementing and cohesion effects. The interface strength is primarily provided by frictional forces. Therefore, when calculating the residual strength parameters of the interface, only the residual friction angle is considered while ignoring the interface cohesion. Table 4 presents the residual friction angles of the cast-in-place and precast concrete-frozen soil interfaces under varying water contents. From the table, it is observed that the residual friction angle of the cast-in-place concrete-frozen soil interface does not show a clear trend with changing water content. Conversely, the residual friction angle of the precast concrete-frozen soil interface generally decreases with an increase in water content. Additionally, both residual friction angles are lower than the peak friction angle, indicating that shear action not only destroys interfacial bonding and cohesive effects but also interfacial frictional effects. This destruction primarily arises from the considerable disruption of the interlocking effect between interface particles.



(a) Cast-in-place concrete-frozen soil interface (b) Precast concrete-frozen soil interface

Fig. 10 Shear strength curve of concrete-frozen soil interface under different water content

Table 3 Interface peak strength parameters under different water content

Initial water content /%	Peak cohesion /kPa		Peak friction angle /°	
	Cast-in-place concrete-frozen soil interface	Precast concrete-frozen soil interface	Cast-in-place concrete-frozen soil interface	Precast concrete-frozen soil interface
12	396.57	—	32.32	36.49
15	414.95	6.04	36.51	36.10
18	329.18	41.43	48.10	33.87
21	264.26	38.13	37.42	31.02
24	126.58	32.48	38.76	29.41

Table 4 Interface residual strength parameters under different water content

Initial water content /%	Residual friction angle /°	
	Cast-in-place concrete-frozen soil interface	Precast concrete-frozen soil interface
12	32.94	21.73
15	29.65	26.40
18	35.50	23.88
21	27.85	22.04
24	29.88	12.55

4. Discussion

This study investigates the mechanical characteristics and distinctions between cast-in-place and precast concrete-frozen soil interfaces, considering the initial water content of the soil as a variable. The results of the examination of both interfaces indicate that the peak strength of the interfaces follows an increasing trend followed by a decrease with rising water content, resembling findings from previous studies on concrete-frozen soil interfaces. Previous research by scholars such as Liu *et al.* (2014), He *et al*. (2018) and others revealed a positive correlation between interface peak strength and water content, with their experimental results aligning with this study in cases of lower water content. However, their experimental soil samples mostly had water content below 21%, neglecting higher water content. Studies by Wen *et al*. (2013) and others indicated that when the soil water content increased from 19% to 21.5%, the ice bond strength at the interface reached its maximum, and the interface strength stabilized. Another study by Ma *et al*. (2021) and colleagues on concrete-frozen soil interface strength at higher water content showed that the overall peak strength decreased when the water content increased from 18% to 27%, similar to the results of this study at higher water content. Analysis suggests that this study, using silty clay consistent with previous research, despite regional variations in the experimental soil samples, has a similar particle composition, developed matrix, and mineral components, leading to comparable physicochemical properties. The main difference lies in the variation of experimental factors;

This study builds on previous research by introducing experimental gradients, enhancing the water content range in the experimental design, and further investigating the mechanical characteristics of interfaces at higher water content. Simultaneously, the sample preparation process differs from previous studies, as this research prefabricated frozen soil samples, making it closer to actual engineering conditions in cold regions and resulting in some differences in experimental outcomes compared to previous studies.

The experimental results suggest that the mechanical characteristics of the cast-in-place concrete-frozen soil interface are markedly superior to those of the precast concrete-frozen soil interface. However, with higher water content, the former undergoes a more pronounced mechanical deterioration, leading to severe strength loss compared to the latter. Consequently, for practical engineering applications, it is more beneficial for stability to employ cast-in-place concrete construction in conditions of higher negative temperatures and lower water content, while precast concrete construction is preferable in conditions of lower negative temperatures and higher water content. It is noteworthy that the experiments reveal the existence of an optimum water content that maximizes the peak strength of the interface. Therefore, in actual construction processes, such as when employing artificial freezing methods, determining the optimal water content for the concrete-frozen soil interface is crucial for engineering construction.

In addition, it is worth noting that the roughness of the interface is a significant factor affecting the characteristics of the frozen soil-structure interface, and the discussion on roughness in this paper has not yet delved into depth. This will be further considered in subsequent studies. At the same time, it should be pointed out that the interface characteristics between concrete and frozen soil are greatly influenced by thermal disturbances, and how to reduce the impact of thermal disturbances on frozen soil remains a topic of concern. Existing research indicates that the addition of nanomaterials, glass fibers, and other substances to the soil can effectively reduce the impact of thermal disturbances on frozen soil (Ahmadi *et al.* 2021a, 2021b; Changizi *et al.* 2022). Therefore, in future studies, it can combine microscopic experiments to further investigate the influence of novel materials on the mechanical properties of the concrete-frozen soil interface.

5. Conclusions

Based on a series of direct shear tests, this study investigated the mechanical properties of the cast-in-place and precast concrete-frozen soil interface under different water contents and analyzed the differences between the two interfaces. The following conclusions are primarily drawn.

(1) The shear stress-displacement curves of cast-in-place and precast concrete-frozen soil interfaces both demonstrate strain-softening behavior. These curves can be divided into three stages: a rapid increase in shear stress, followed by post-peak shear stress softening, and ultimately reaching a residual stable. The periodic attenuation phenomenon in the shear stress-displacement curves is more noticeable in the case of the precast concrete-frozen soil interface.

(2) The peak strength of cast-in-place and precast concrete-frozen soil interfaces exhibits an initial increase followed by a decrease with rising water content. Conversely, the residual strength is relatively less affected by changes in water content. Both the peak and residual strengths of these interfaces demonstrate a linear positive correlation with normal stress, the ice bond strength proves to be less susceptible to variations in normal stress.

(3) The peak cohesion and peak friction angle of the cast-in-place concrete-frozen soil interface follow a pattern of initially increasing and then decreasing with increasing water content. The peak cohesion reaches a maximum value of 414.95 kPa at approximately 15% water content, while the peak friction angle achieves a maximum value of 48.10° at around 18% water content. Similarly, the peak cohesion of the precast concrete-frozen soil also follows a similar trend, with a peak value of 41.43 kPa obtained at around 18% water content. The peak friction angle of the precast concrete-frozen soil is found to be significantly and negatively correlated with water content.

(4) The mechanical properties of the cast-in-place concrete-frozen soil interface surpasses that of the precast concrete-frozen soil interface. However, with higher water content, the deterioration trend of mechanical properties of the former is much higher than that of the latter. Consequently, in practical engineering applications, cast-in-place concrete construction is used in conditions of higher negative temperatures and lower water content, whereas precast concrete construction is chosen in conditions of lower negative temperatures and higher water content.

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